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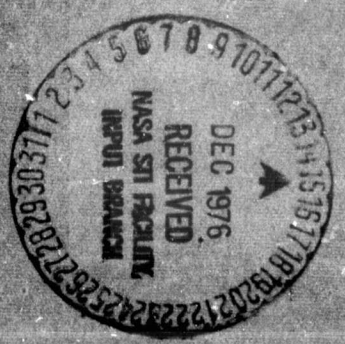
ANALYSIS OF SKYLAB FOLLOW-ON ORBITAL NEUTRON ENVIRONMENTAL DATA



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INTRODUCTION

Martin Marietta has processed and analyzed a total of 54 solid dielectric track recorders. The processing, which included HF acid etching of the mica track recorders and NaOH base etching of the cellulose nitrate track recorders, preceded the actual counting of tracks. Subsequent analysis of the data utilized the data base and techniques developed previously by Martin Marietta for Skylab Experiment ED76.

The impact of this analysis on the data and results of ED76 as described in MMA report ED-2002-1733 (30 June 1975) has been assessed. Comparison of these results with previously published orbital neutron radiation data has been made.

EXPERIMENTAL

A. PRINCIPLES OF NEUTRON DETECTION

This experiment utilized a neutron detector which employed two passive neutron detection schemes based on dielectric track recorders: (a) cellulose nitrate plastic was used in conjunction with ^{10}B targets to record particles from the ^{10}B $(n,\alpha)^{7}Li$ reaction, and (b) natural musconite mica was used to record fission fragments which resulted from fission in ^{235}U, ^{238}U, ^{232}Th, and ^{209}Bi targets. Mica-^{235}U and plastic-^{10}B detectors covered by 0.25 mm Cd absorbers were also included. The Cd-covered detectors give additional information about the low energy neutron spectrum because Cd strongly absorbs neutrons below about 0.5 eV. Consequently, only the fraction of the neutron density above this energy is registered. The response of the ^{10}B detectors is inversely proportional to neutron velocity and this is a measure of neutron density. The ^{235}U has a similar response at neutron energies below 1 ev but, unlike the ^{10}B, the response of the ^{235}U to high energy particles ($\geq$1 Mev) is not negligible. The ^{238}U and ^{232}Th show fission thresholds at about 0.5 and 1.5 Mev respectively, and the fission of ^{209}Bi is only appreciable above about 50 Mev, so these three detectors are used to characterize the high energy particle flux. The principal limitation of the fission detectors is that they also respond to high energy protons as well as neutrons.

B. PRINCIPLES OF PROTON DETECTION

Ilford G-5 emulsions flown as part of the neutron detector have been analyzed to yield proton flux data. The proton fluxes as a function of energy are about an order of magnitude lower than those observed on Skylab.

C. INSTRUMENT DESCRIPTION

Figure 1 is a schematic diagram of the neutron and proton flight detector. Twelve cylindrical depressions with diameter of 15.9 mm (0.625") and depth of 2.54 mm (0.100") were milled in an aluminum disc of 3.18 mm (0.125"). These depressions were filled with foil/recorder combinations as tabulated in Table I. Additionally, a rectangular depression was milled in the center of the disc; half this depression was allocated to proton-sensitive emulsions, and the other half accommodated a ^{209}Bi/Mica sandwich.

D. DATA ANALYSIS

The mica was annealed for 1 hour at 625°C prior to flight in order to remove background from fossil ^{238}U spontaneous fission tracks which are present in natural mica. However, because some very short (<1 micron) residual tracks are left even after annealing, the detectors were also pre-etched for 4 hours in HF prior to flight; thus any short fossil tracks were readily recognized because they were much wider than fresh tracks.

In order to reveal the tracks for viewing in an optical microscope, the mica was etched for about 1 hour in 48% HF at about 50°C. Elevated etching tem- apertures were used to produce relatively wide tracks (10-20 microns) in order to be able to scan at low magnification. The mica was scanned at low magnification (300-500 micron wide fields of view) in transmitted light. Typical track densities in the fission recorders ranged from 2(Bi) to 500 $\left(^{235}U\right)$ tracks/cm^2. A background measurement on the side of one of the mica detectors not facing a target foil gave 0.5 tracks/cm^2. This is negligible and background correction has not been applied to the data.

The cellulose nitrate was etched for 4 hours in a mixture of 7 parts of 6.25N NaOH solution and 5 parts 12% NaOCl solution at 40°C. The bath temperature was regulated to $\pm$0.2°C and continuously monitored. Track densities

were measured in fields of view of 100μ width using transmitted light. Typical track densities were around $10^3/cm^2$.

E. CALIBRATION

The measured track densities can be converted to fission (or capture for ^{10}B) rates (1,2):

(1) $f\rho = \epsilon PTG$

where P is the fission/capture rate in reactions per gram of target element per second, T is the exposure time, ϵ is the detector efficiency (in g/cm^2) for a target and detector in contract (2π geometry), G is a geometrical factor allowing for the small gap between the track detector and target, and f is a self-shielding correction required for the ^{10}B and ^{235}U because these nuclei are strong absorbers of low energy neutrons. The origin and determination of these quantities is described in detail in references 3 and 4. The discussion below is only intended to supplement these sources. Table II gives the values adopted for the various parameters.

For the fission detectors ϵ is approximately equal to R/2 where R/2 is the range of a single fission fragment in the target. The values given in Table II for ^{235}U were obtained experimentally by measuring the track densities in mica exposed to natural and depleted U metal foils in a well thermalized and standardized neutron flux (1). The efficiency for ^{238}Th metal is assumed to be equal to that for ^{235}U. The value for ^{209}Bi was calculated assuming that the fission fragment range in g/cm^2 is proportional to the square root of the atomic number and the value for ^{238}U was assumed to be equal to that for ^{235}U.

The efficiency for the ^{10}B targets is based on samples of the target material and plastic placed in contact in air and exposed to a well-thermalized

neutron flux monitored using a ^{235}U-mica track detector. The value of ϵ for ^{10}B given in Table II is about 30% lower than that for the targets used in the lunar neutron capture rate measurements of Woolum et. al. (2); however, this is reasonable because different target materials were used and the quality of the lunar targets was known to be better.

The self-shielding factors f were evaluated by the methods described in references 1 and 2. These methods are independent of any detailed assumptions about the low energy neutron spectrum. The only difference is that a theoretical calculation of the self-shielding of the ^{10}B targets for thermal and I/E neutron spectra was used here in place of the empirical values used in Woolum et al (2). The ^{10}B targets used for ASTP were slightly thicker but the geometry of the detectors had less self-shielding; consequently the value of f is very similar to that used in Woolum et al.

No geometry corrections for the detectors have been made.

RESULTS

Table III gives the measured time-integrated fission or capture rates for the track detectors. The errors quoted in Table III are the best estimate of the overall accuracy of the capture rates and are taken from Quist, et. al.[5]

INTERPRETATION

The measured fission and capture rates can be used to determine a neutron energy spectrum. The method used is that of unfolding a neutron spectrum from the threshold detectors used to measure the fission and capture rates. There are several problems related to this procedure: (1) one must initially assume some energy spectrum; (2) the proton induced contributions must be separated from the measured rates; (3) there are large uncertainties in the high energy portion of the cross-sections used in the unfolding process.

The neutron spectrum may be unfolded from the track detector measurements through the use of the following set of equations, one for each reaction measured, 6,7,8.

$$A_i = \int_{E_1}^{E_2} \tau_i(E)\emptyset(E)dE,$$

where A_i is the measured rates, $\tau_i(E)$ is the formation cross section of the particular fission rate, A_i, as a function of energy, and $\emptyset(E)dE$ is the desired differential neutron flux. To solve this equation for $\emptyset(E)dE$ one must resort to an iterative technique.

The procedure used here follows that of the computer code SPECTRA[9]. The SPECTRA method uses N flux points of unknown value and assumes that the value of the flux between these unknown points varies linearly. If the number of activation data available are greater or equal to the number of flux points

then the unknown flux values are determined directly by minimizing the expression.

$$Q = \sum_{i=1}^{n} (A_i - A_{ci})^2$$

where A_i is the measured activity, and

$$A_{ci} = \sum_{j=1}^{n} c_{ij}\phi_j = \int_0^{\infty} \sigma_i(E)\phi(E)dE$$

In all practical cases, however, the number of activation data are much smaller than the desired number of flux points. This difficulty is overcome by a first order approximation to the flux values ϕ_{jo} and the following expression is minimized

$$Q' = \sum_{i=1}^{n} W_i(A_i - A_{ci})^2 + \int_{j=1}^{n} W_j(\phi_j - \phi_{jo})^2$$

where W_i and W_j are weighting functions. The obtained solution of ϕ_j is then used as input to the next iteration. The iteration continues until the absolute value of Q' has reached a prefixed limit.

The assumed initial neutron energy spectrum and the ^{209}Bi cross section was obtained from Quist et.al[5]. The ^{235}U and ^{235}U and ^{232}Th cross section used were obtained in a manner described in Perry, Simmons and Gilmore[10]. The ^{10}B capture cross section was obtained from the BNL neutron book[11].

The proton induced fission correction is about 10%[12] of that on Skylab as defined by Quist, et. al[3] and therefore, would result in only about a 5% adjustment to the number of events observed in conjunction with the current foils. This proton correction has been ignored in unfolding the neutron spectrum.

The unfolded neutron spectrum is shown in Figure 2.

Table I

Tabulated below are the contents of the milled depresions in the detector disc described in the text. All foils had a nominal thickness of .001 inch, the cellulose nitrate has an approximate thiciness of .001 inch, and the mica was cleaned to thicknesses of about .001-.003 inches. Some cylinders were filled with multiple foil/recorder sandwiches; the exact numbers are shown below. Unused volume in partly full cylinders was filled with mica shims to insure that foils and recorders were in physical contact and not able to move with respect to each other.

Cylinder #	Foil	Recorder	Number of Foil/Recorder Sandwiches
1	^{232}Th	Mica	4
2	^{10}B	CN	1
3	^{10}B	CN	1
4	^{10}B	CN	1
5	^{238}U	Mica	4
6	^{235}U/Cd	Mica	2
7	^{232}Th	Mica	4
8	^{235}U	Mica	1
9	^{235}U	Mica	2
10	^{235}U	Mica	1
11	^{238}U	Mica	4
12	^{10}B/Cd	CN	1
13	^{209}Bi (Plus proton emulsions as described in text)	Mica	1

Table II

Calibration Constants for the Detectors

Detector	Self-Shielding f	Efficiency ϵ (mg/cm^2)	Geometry G
^{10}B	1.33 ± .12	0.12 ± .02	1.0
^{10}B + Cd	1.10 ± .02	0.11 ± .02	1.0
^{235}U	1.13 ± .07	4.28 ± .17	1.0
^{235}U + Cd	1.0	4.28 ± .17	1.0
^{238}U	1.0	4.56 ± .2	1.0
^{232}Th	1.0	4.28 ± .17	1.0
^{209}Bi	1.0	4.28 ± .17	1.0

Table III

Total Fission/Capture Rates

Detectors	(tr/cm^2)	(Fissions or capture)/g
^{10}B	$1.31 \pm 0.13 \times 10^3$	$1.45 \pm 0.31 \times 10^7$
^{10}B + Cd	$7.02 \pm .054 \times 10^2$	$7.02 \pm 1.39 \times 10^6$
^{235}U	$4.73 \pm 0.22 \times 10^2$	$1.25 \pm 0.11 \times 10^5$
^{235}U + Cd	$1.22 \pm 0.11 \times 10^2$	$2.85 \pm 0.28 \times 10^4$
^{238}U	$8.83 \pm 0.94 \times 10^1$	$2.06 \pm 0.23 \times 10^4$
^{232}Th	$2.08 \pm 0.46 \times 10^1$	$4.86 \pm 1.09 \times 10^3$
^{209}Bi	1.97 ± 1.40	$4.32 \pm 3.08 \times 10^2$

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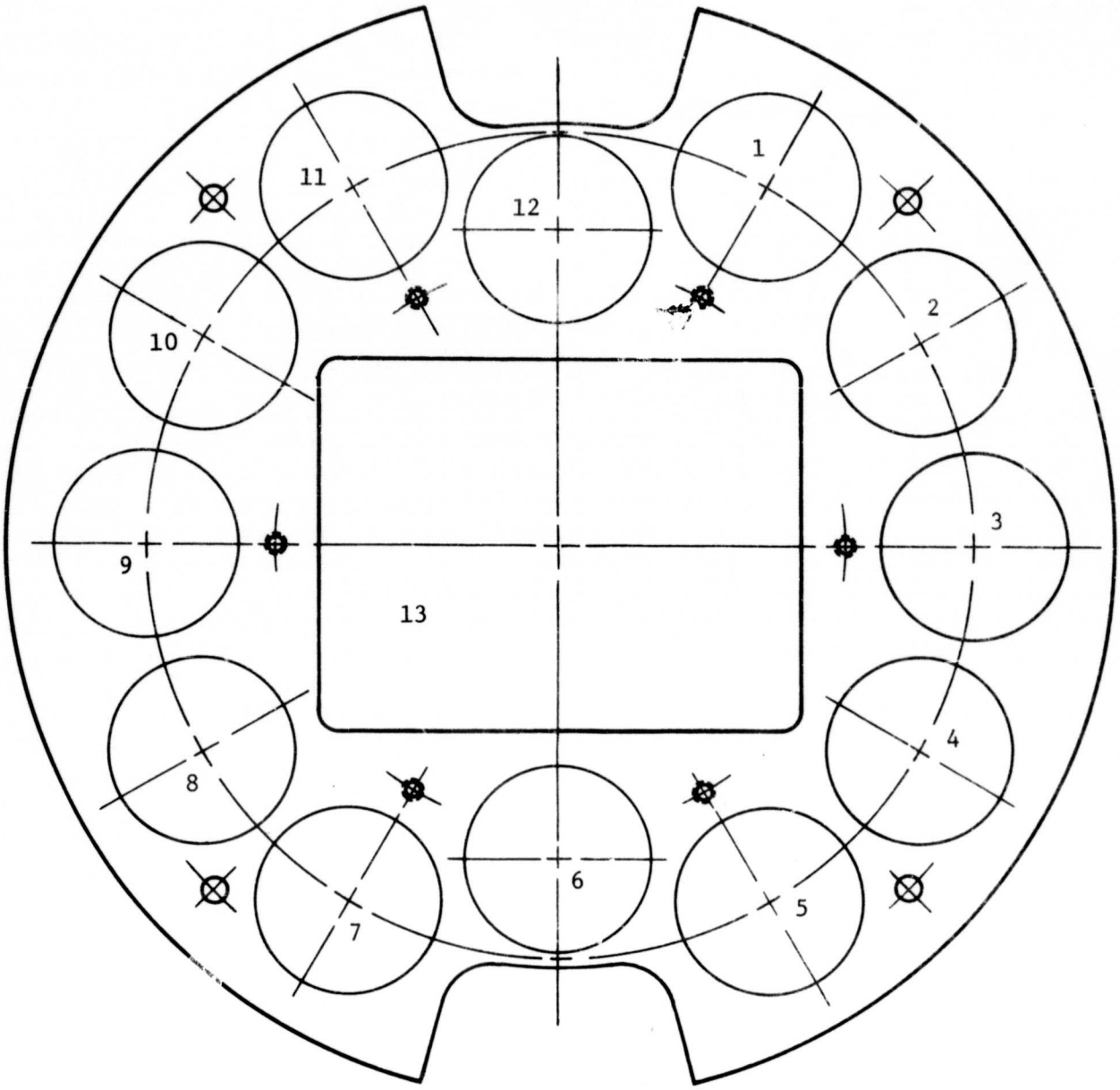

Figure 1 Foil/Recorder Sandwich Holder

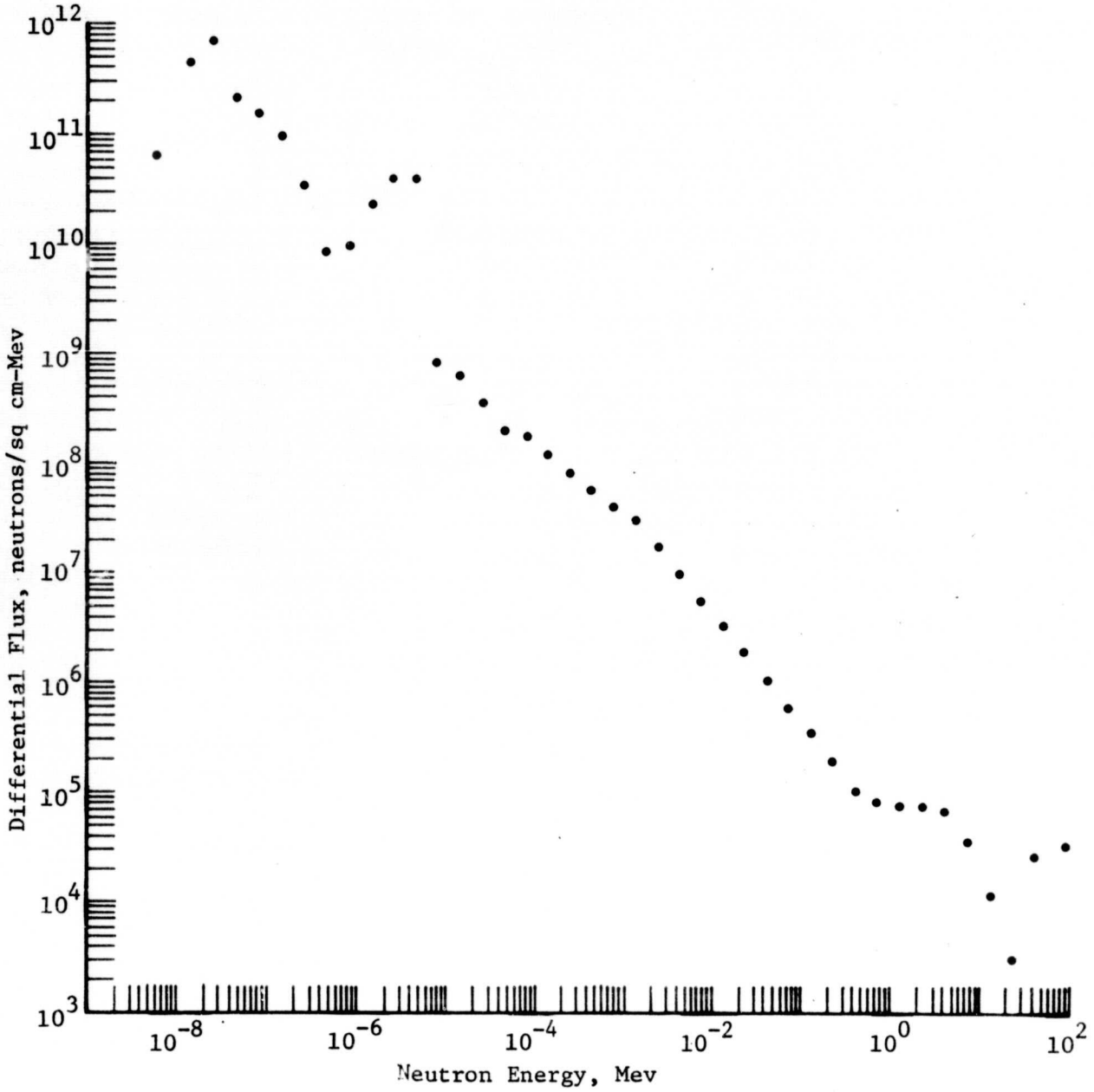

Figure 2 The Unfolded Differential Neutron Spectrum